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# The cyclotron gas stopper project at the NSCL

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**Abstract** Gas stopping is becoming the method of choice for converting beams of rare isotopes obtained via projectile fragmentation and in-flight separation into low-energy beams. These beams allow ISOL-type experiments, such as mass measurements with traps or laser spectroscopy, to be performed with projectile fragmentation products. Current gas stopper systems for high-energy beams are based on linear gas cells filled with 0.1-1 bar of helium. While already used successfully for experiments, it was found that space charge effects induced by the ionization of the helium atoms during the stopping process pose a limit on the maximum beam rate that can be used. Furthermore, the extraction time of stopped ions from these devices can exceed 100 ms causing substantial decay losses for very short-lived isotopes. To avoid these limitations, a new type of gas stopper is being developed at the NSCL/MSU. The new system is based on a cyclotron-type magnet with a stopping chamber filled with Helium buffer gas at low pressure. RF-guiding techniques are used to extract the ions. The space charge effects are considerably reduced by the large volume and due to a separation between the stopping region and the region of highest ionization. Cyclotron gas stopper systems of different sizes and with different magnetic field strengths and field shapes are presently investigated.

**Keywords** Cyclotron · Ion beam stopper

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## 1 Introduction

Rare isotope production via relativistic projectile fragmentation and in-flight separation produces nuclides with short half-lives without limitations due to element selectivity. Several fragmentation facilities exist worldwide. At all of them slowing down and stopping of fast rare isotope beams is under development. The goal is to produce low-energy beams that can then be used for ISOL-type experiments, *i.e.* experiments using low-energy radioactive beams with small phase space volume, such as mass measurements with traps or laser spectroscopy, or post-accelerated for low-energy reaction studies. LEBIT [1], installed at the NSCL at MSU, was the first to demonstrate that relativistic (150 MeV/u) rare isotope beams can be thermalized to low-energy ( $\sim 5$  keV) and be used for precision experiments. A number of high-precision mass measurements have already been performed, for example on  $^{38}\text{Ca}$  [2],  $^{66}\text{As}$ ,  $^{64}\text{Ge}$ ,  $^{69}\text{Se}$ , and  $^{40,42}\text{S}$ . At GSI, a stopping test with a large linear gas cell [3] was successfully carried out. At RIKEN, a laser spectroscopy experiment with trapped radioactive Be ions, obtained via gas stopping of fast fragments, was performed recently [4].

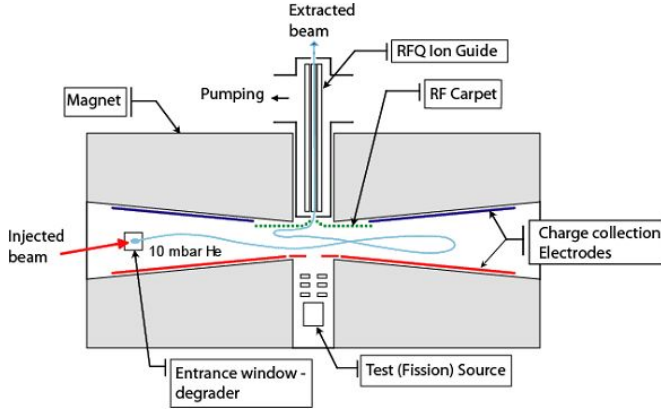
Present gas stopping schemes are all based on the slowing down of the fast fragments in solid degraders and a final stopping of the ions in a chamber filled with helium gas. Remaining singly or doubly-charged, ions are guided out of the gas using electric fields and gas flow and then prepared into a low-emittance, low-energy ion-beam by means of radio-frequency (RF) ion guiding techniques. Different concepts are applied for the ion extraction. In the case of low-pressure gas cells ( $< 300$  mbar He) a combination of electrostatic and RF potentials is often employed. The gas cell [5] of LEBIT is operated at high pressure (1 bar He). Static electric fields guide the ions to an extraction nozzle where the force provided by the gas flow transports them out of the gas cell.

A rate-dependent efficiency for linear gas cells has been observed in a variety of systems [6, 7, 8, 9]. Extraction efficiencies of existing linear gas cells decrease precipitously with the ionization rate density (rate of generation of ion pairs (IP) per volume) inside the gas cell. The decrease in efficiency is attributed to space-charge effects, which lead to ion losses inside the gas cell. Next generation facilities will offer exotic beam rates of  $10^9$ /s, requiring the efficient handling of ionization rate densities of about  $10^{11}$  IP/cm<sup>3</sup>/s. This is not achievable with existing gas cells without a significant loss in efficiency.

For the stopping of rare isotope beams with an energy of about 100 MeV/u, linear gas cells need to be operated with a pressure-length product of typically  $p \cdot L = 0.5$  bar·m. Limited by the maximum applicable electric field for ion transport and extraction inside the gas cell the average extraction time is about 100 ms. Such long extraction times do not match the advantage of fast-beam production and lead to decay losses.

In order to maximize the benefit of the gas stopping approach, the following requirements have to be fulfilled:

- Short extraction times. In order to minimize decay losses the extraction time should be comparable or shorter than the shortest half-life of the ions to be studied. Extraction times of 10 ms or less are desirable.



**Fig. 1** Schematic view of the cyclotron gas stopper showing the main components of the system. A cyclotron-type focusing magnet contains a vacuum chamber filled with helium at low pressure, a beam degrader, charge collection electrodes, and an RF carpet for ion extraction.

- Efficient stopping and extraction at high beam intensities. Next-generation facilities will provide rare isotope beam intensities of up to  $10^9$  /s, many orders of magnitude higher than available at present fragmentation facilities.
- Applicability to all fragment beams. In order to be universal, the gas stopper needs to be able to handle beams of isotopes with largely different charges  $Z$  and neutron-to-proton ratios.

A new concept, the cyclotron gas stopper, promises to fulfill these requirements and to overcome the limitations of linear gas stoppers [10]. Such a system, based on a cyclotron-type focusing magnet with a gas-filled stopping chamber and using radio-frequency (RF) ion guiding techniques for ion extraction, is presently under development at the NSCL.

## 2 Concept

Figure 1 presents the main components of the cyclotron gas stopper. Ions injected into the system will first interact with a solid degrader and then be slowed down in helium gas at low pressure. The focusing properties of the magnet confine the ions during the deceleration process. The ions are finally extracted by means of static electric fields, an RF carpet [6] and radio-frequency ion guides.

With a long stopping path, a low pressure may be used inside the cyclotron gas stopper. This low pressure will allow for a fast drift inside the magnet and a fast extraction, which will match the advantages of fast-beam production. The larger volume as compared to linear gas cells and a separation of the stopping region from the primary ionization directly contribute to the minimization of space charge effects.

A similar concept has been used for the production of antiprotonic, pionic and muonic atoms [11] and has also been discussed for the stopping of light ions [12]. The benefit of this concept for the stopping of intense rare isotope beams was first shown in simulations performed at the NSCL/MSU [10].

An RF carpet has already been used successfully [6] in a linear gas cell. Because of its low pressure ( $< 20$  mbar) the cyclotron gas stopper provides an ideal environment for the operation of RF carpets. The modest damping of the ion motion, as compared to high-pressure linear gas cells, allows carpets to be used with a relatively large pitch and low voltages, while still providing a strong repelling force. Static potentials will be used to guide the ions onto the carpet surface and to the extraction orifice.

### 3 Mechanical design

The mechanical design of the cyclotron gas stopper is underway and will be based on detailed simulations discussed below. At the present stage of design a vertically oriented magnet system is favored. Superferric magnets have been designed that produce peak magnetic fields between 1.6 and 3 T. Two separated coil packages will be used in order to be able to open the yoke, facilitating the access to the inner part of the system. Figure 2 presents a conceptual design of one of the systems under consideration. The vertical arrangement has advantages in particular for the extraction and transport of the low-energy beams out of the fringe field. The magnet system will house a cryogenically cooled vacuum chamber, filled with helium gas at a typical pressure of 10 mbar or less. The beam degrader and beam monitors are inserted radially. The diameters of the systems presently considered range from 3–4 m with beam injection radii between 0.7–1.5 m. Options considered are sector fields for stronger transverse focusing, different field shapes, and the use of multiple degraders.

### 4 Beam stopping simulations

Various detailed numerical calculations based on realistic magnetic fields are being carried out to optimize and characterize the system. They include the Lorentz force, energy loss, charge-exchange collisions, and small-angle multiple-scattering [13]. The simulations are being performed for light to heavy isotopes of key nuclides with different  $A/Z$ . Bromine isotopes  $^{70,79,94}\text{Br}$  were chosen to represent the central region of the nuclear chart. Iodine isotopes  $^{108,127,144}\text{I}$  for heavier isotopes and  $^{6,9,11}\text{Li}$  for the very lighter mass region. The choice of these nuclides was also based on the availability of data for low-energy charge-exchange cross sections with helium [14, 15].

A C++ version [16] of the ATIMA [17] code is used to model the interaction of the incoming beam with the degrader. ATIMA calculates the stopping power, the energy loss, the energy-loss straggling, the angular straggling, the range, and the range straggling.

Different magnet sizes and field shapes are under investigation. Weakly focusing and a sector-field magnet are considered. Examples for the resulting

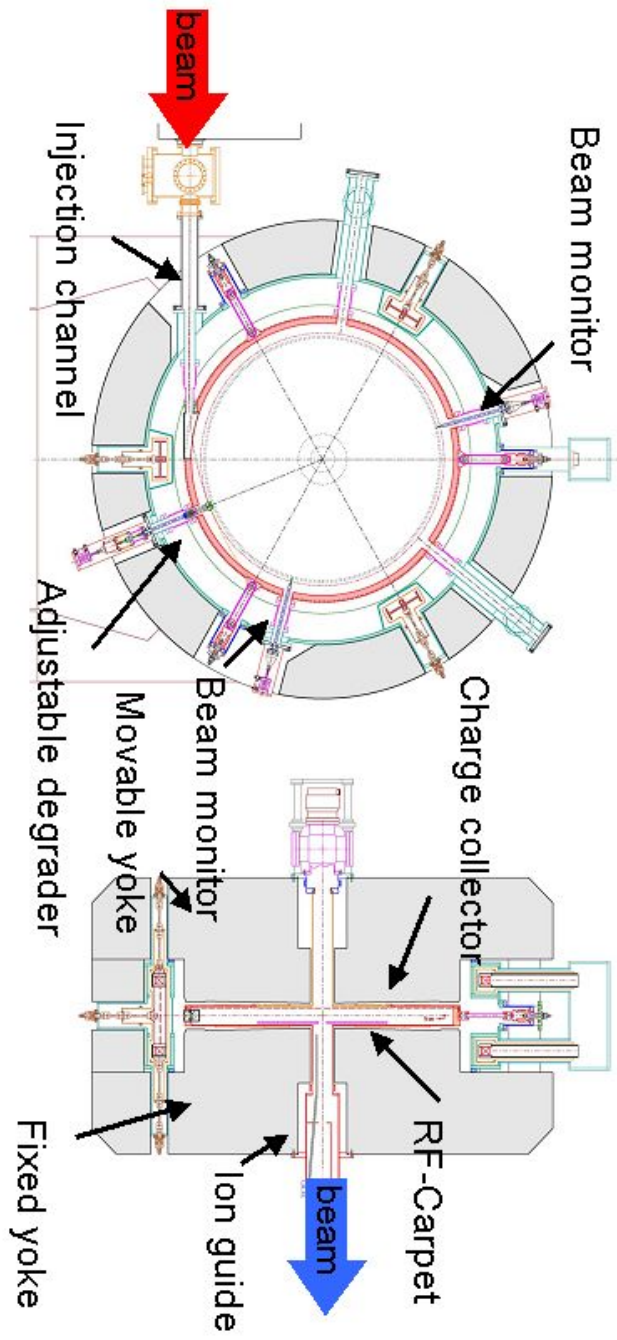
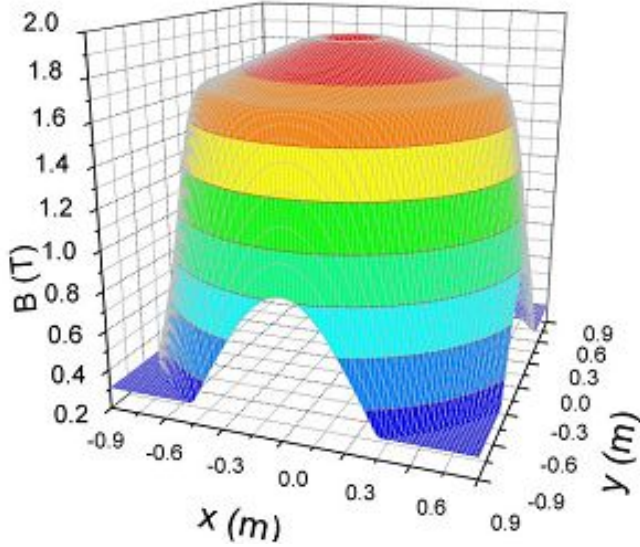


Fig. 2 Design concept of a vertical superconducting magnet under consideration.



**Fig. 3** Realistic magnetic fields obtained in a weakly focusing magnet (left) and a sector-field magnet (right), calculated with the TOSCA code.

fields are shown in Figure 3. Both systems allow ions to be stopped effectively. The sector-field magnet offers some advantages since the injection for isotopes with large  $A/Z$  (high-rigidity) is simplified.

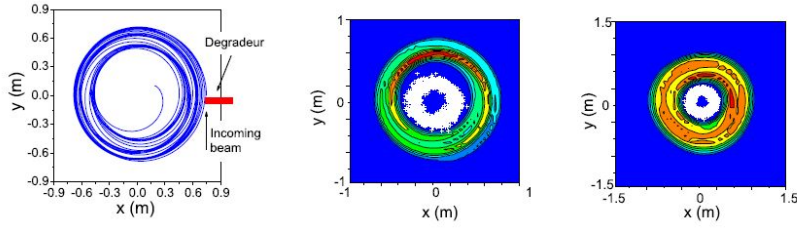
Beam simulations were for example performed for  $^{79}\text{Br}$  isotopes with 100 MeV/u before the degrader in a weakly focusing magnet with  $B_{max} = 2$  T and with 60 MeV/u in the case of the sector-field magnet with  $B_{max} = 2.6$  T. In both cases helium gas pressure of about 10 mbar was used. Figure 4 shows typical results. On the left the trajectory of a single ion inside the weakly focusing magnet is presented. The two figures on the right show stopped ion distributions (crosses) together with energy loss (ionization) densities (colored/greyscale areas) inside the gas. A key advantage of the cyclotron gas stopper is that there is a separation in-between the region of highest ionization and the central region where the ions stop. Compared to linear stoppers this leads to a large reduction of space charge effects.

Stopping and extraction efficiencies higher than 95 % have been achieved for the bromine beams so far investigated. The systematic exploration of the stopping properties for other rare isotope beams is on its way.

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**Fig. 4** Trajectory of a single  $^{79}\text{Br}$  ion with an energy of 610 MeV after the degrader inside the weakly focusing magnet filled with 10 mbar He (left). Energy deposition and stopped ion distribution (crosses) for a weakly focusing magnet (middle) and a sector-field magnet (right).

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